Neutron Lifetime From Beam Experiments

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Solvay Workshop 2014

Outline of Presentation

- A brief introduction to the neutron lifetime
- Status of current beam measurements
    - J-PARC measurement
    - BL2 at NIST
- Future beam measurements
    - BL3 at NIST
- Conclusions

V_{ud} and the CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \boxed{\begin{matrix} V_{ud} & V_{us} & V_{ub} \end{matrix}} \\ \begin{matrix} V_{cd} & V_{cs} & V_{cb} \end{matrix} \\ \begin{matrix} V_{td} & V_{ts} & V_{tb} \end{matrix} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Measurements of τ_n and β-decay angular correlation coefficients yield $|V_{ud}|$:

$$|V_{ud}|^2 = \frac{4908.7(1.9)\ \mathrm{sec}}{\tau_n(1+3g_A^2)} \qquad g_A \equiv G_A/G_V$$

Measurements of *ft* values for superallowed $0^+ \rightarrow 0^+$ β-decay also yield $|V_{ud}|$:

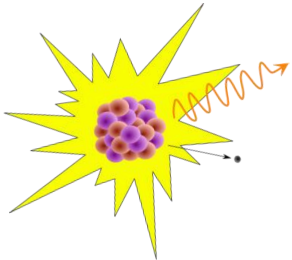
$$|V_{ud}|^2 = \frac{2984.48(5)\,\mathrm{sec}}{ft(1+\mathrm{RC})}$$

How to Measure τ_n ... $N(t) = N_0 e^{-t/\tau_n}$

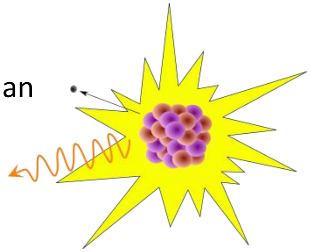
Direct Observation of Exponential Decay:

Observe the decay rate of N_0 neutrons and the slope of

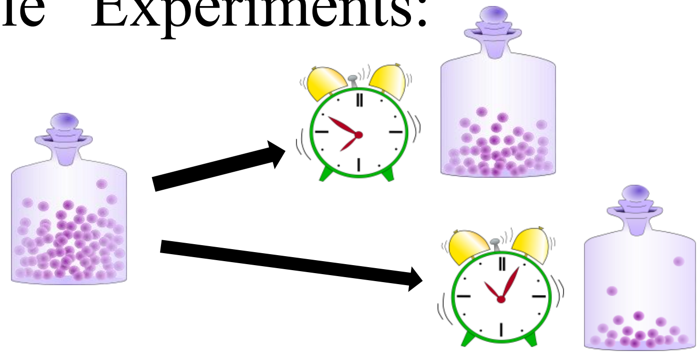
$\ln\left(\frac{\partial N(t)}{\partial t}\right)$ is $-1/\tau_n$



Similar in principle to Freshman Physics Majors measuring radionuclide half lives
-- only a lot harder.



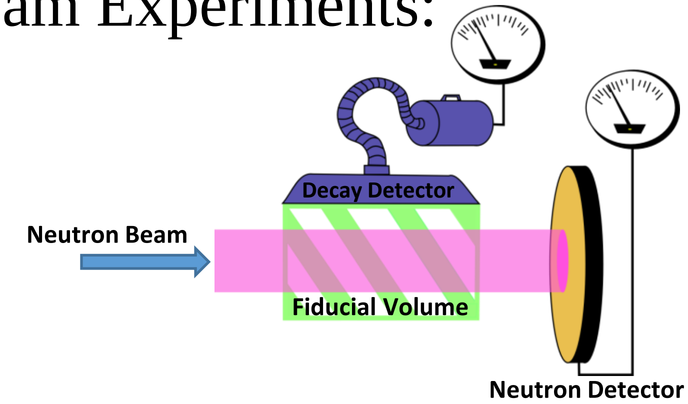
"Bottle" Experiments:



Form two identical ensembles of neutrons and then count how many are left after different times.

$$\frac{N(t_1)}{N(t_2)} = e^{-(t_1-t_2)/\tau_n}$$

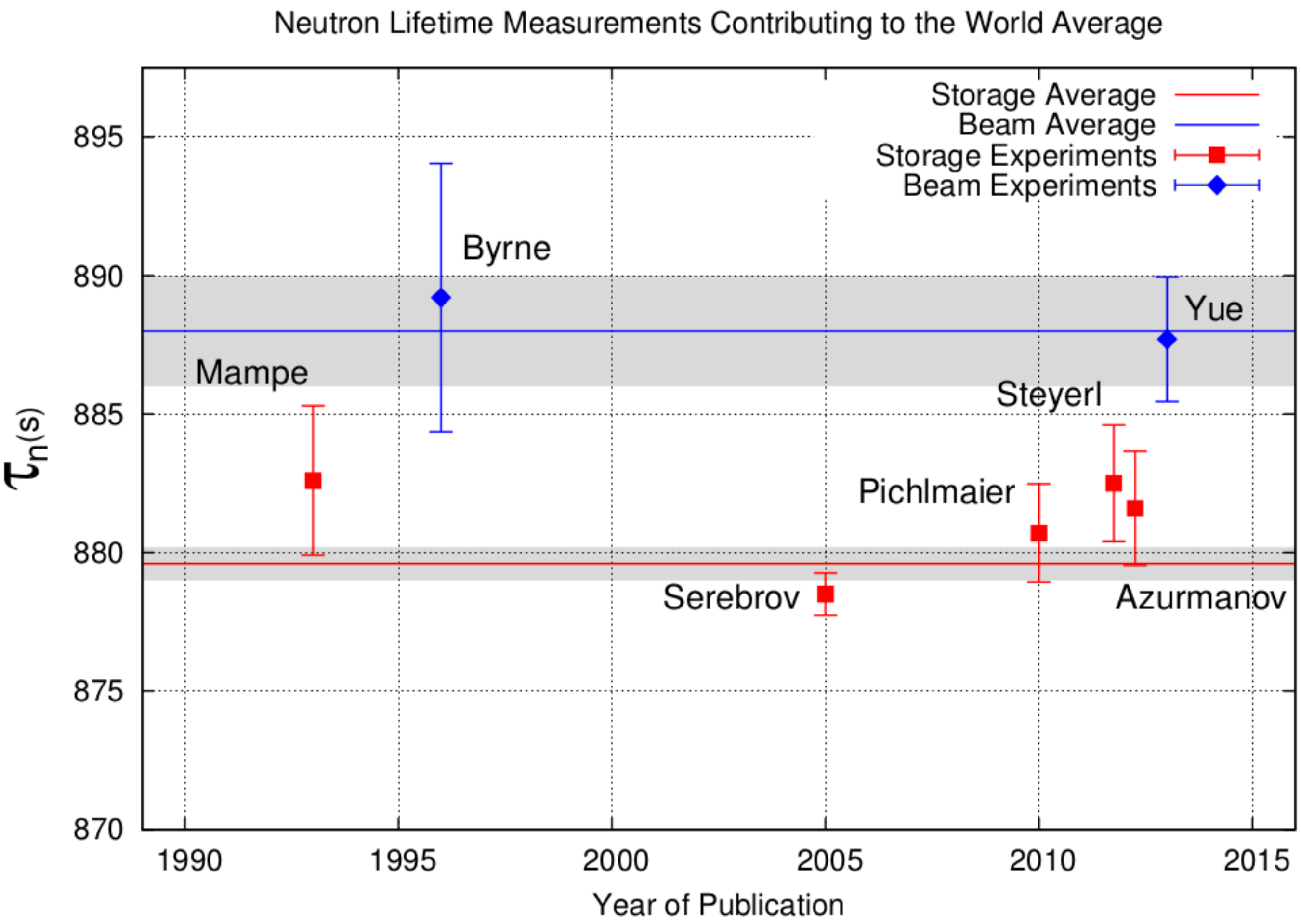
Beam Experiments:



Decay rates within a fiducial volume are measured for a beam of well known fluence.

$$\frac{\partial N(t)}{\partial t} = -N/\tau_n$$

The State of the Neutron Lifetime



Beam Average

$$\tau_n = 888.0 \pm 2.1s$$

Storage Average

$$\tau_n = 879.6 \pm 0.8s$$

Note: This average contains result from Yue et al
Phys. Rev. Lett. 111, 222501 (2013)

The Present

Precise measurement of neutron lifetime with pulsed neutron beam at J-PARC

Kenji MISHIMA (KEK)

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R. Katayama[1], M. Kitaguch[5], R. Kitahara[6], K. Mishima[3], H. Oide[7],
H. Otono[8], R. Sakakibara[2], Y. Seki[9], T. Shima[10], H. M. Shimizu[2],
T. Sugino[2], N. Sumi[11], H. Sumino[12], K. Taketani[3], G. Tanaka[11],
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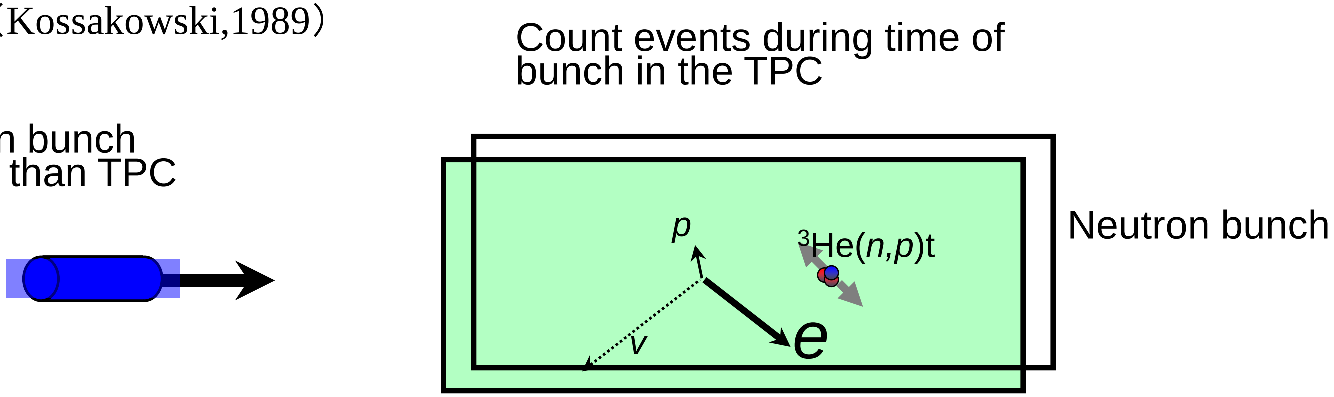
Univ. of Tokyo[1], Nagoya Univ.[2], KEK[3], ICR, Kyoto Univ.[4], KMI, Nagoya Univ.[5], Kyoto Univ.[6], CERN[7], RCAPP, Kyushu Univ.[8], RIKEN[9], RCNP, Osaka Univ.[10], Kyushu Univ.[11], GCRC, Univ. of Tokyo[12], ICEPP, Univ. of Tokyo[13]

Principle of our experiment

Cold neutrons are injected into a TPC.
The neutron β-decay and the ^{3}He(n,p)^{3}H reaction are measured simultaneously.

Principle （Kossakowski,1989）


Count events during time of bunch in the TPC

Neutron bunch shorter than TPC

Neutron bunch

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta}\right)$$

β-decay $S_\beta = \epsilon_e N \frac{L}{\tau_n v}$

^{3}He(n,p)^{3}H $S_n = \epsilon_n N \rho \sigma L$

τ_n : lifetime of neutron
v : velocity of neutron
ε_e : detection efficiency of electron

ε_n : detection efficiency of ^{3}He reaction
ρ : density of ^{3}He
σ : cross section of ^{3}He reaction

$$\sigma v = \sigma_0 v_0$$

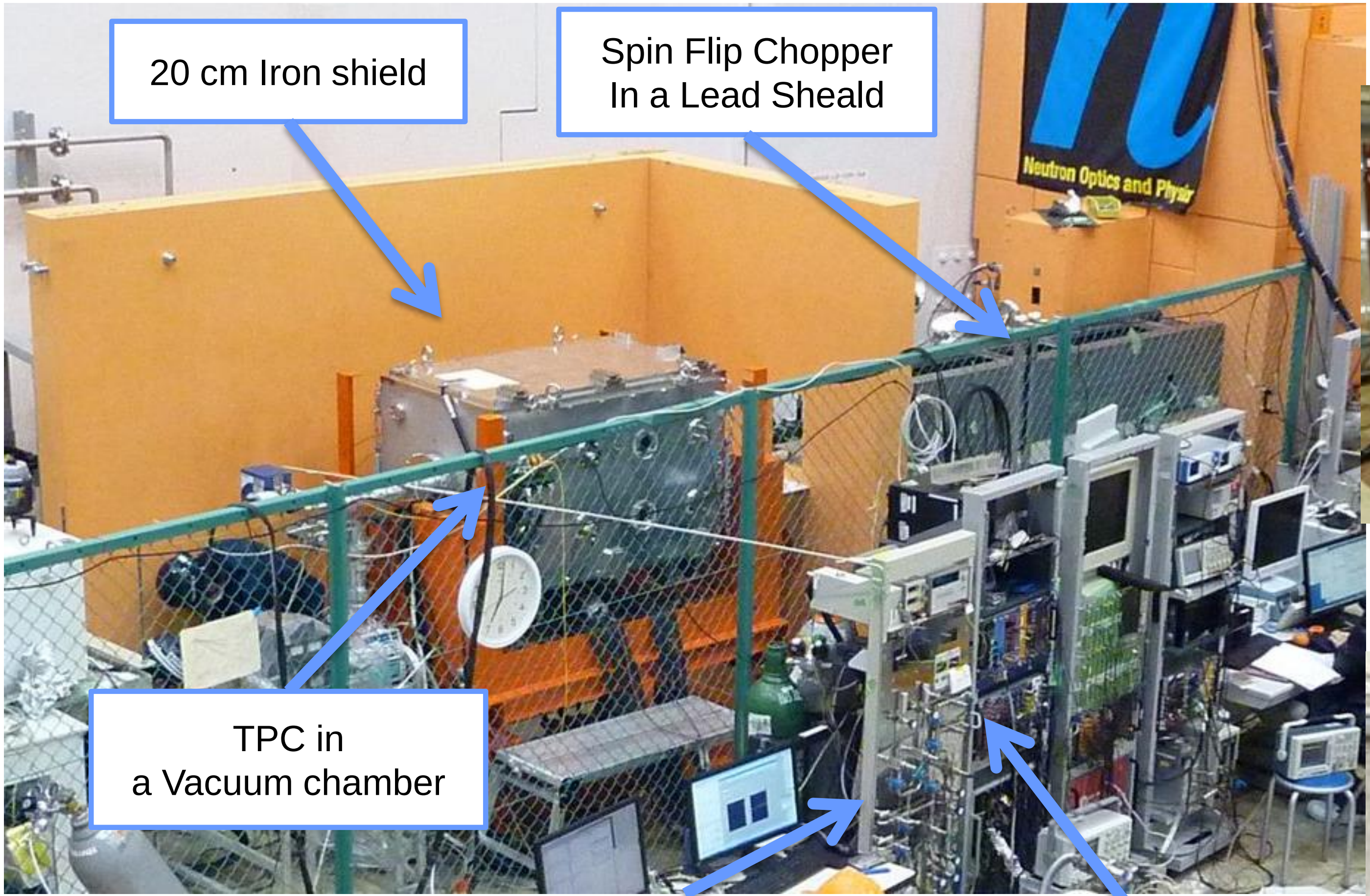
σ_0=cross section@v_0, v_0=2200[m/s]

This method is free from the uncertainties due to external flux monitor, wall loss, depolarization, etc.

Our goal is measurement with 1 sec uncertainty.

Setup

Set up of our experiment in “NOP” beam line.



20 cm Iron shield

Spin Flip Chopper
In a Lead Sheald

TPC in
a Vacuum chamber

Gas line

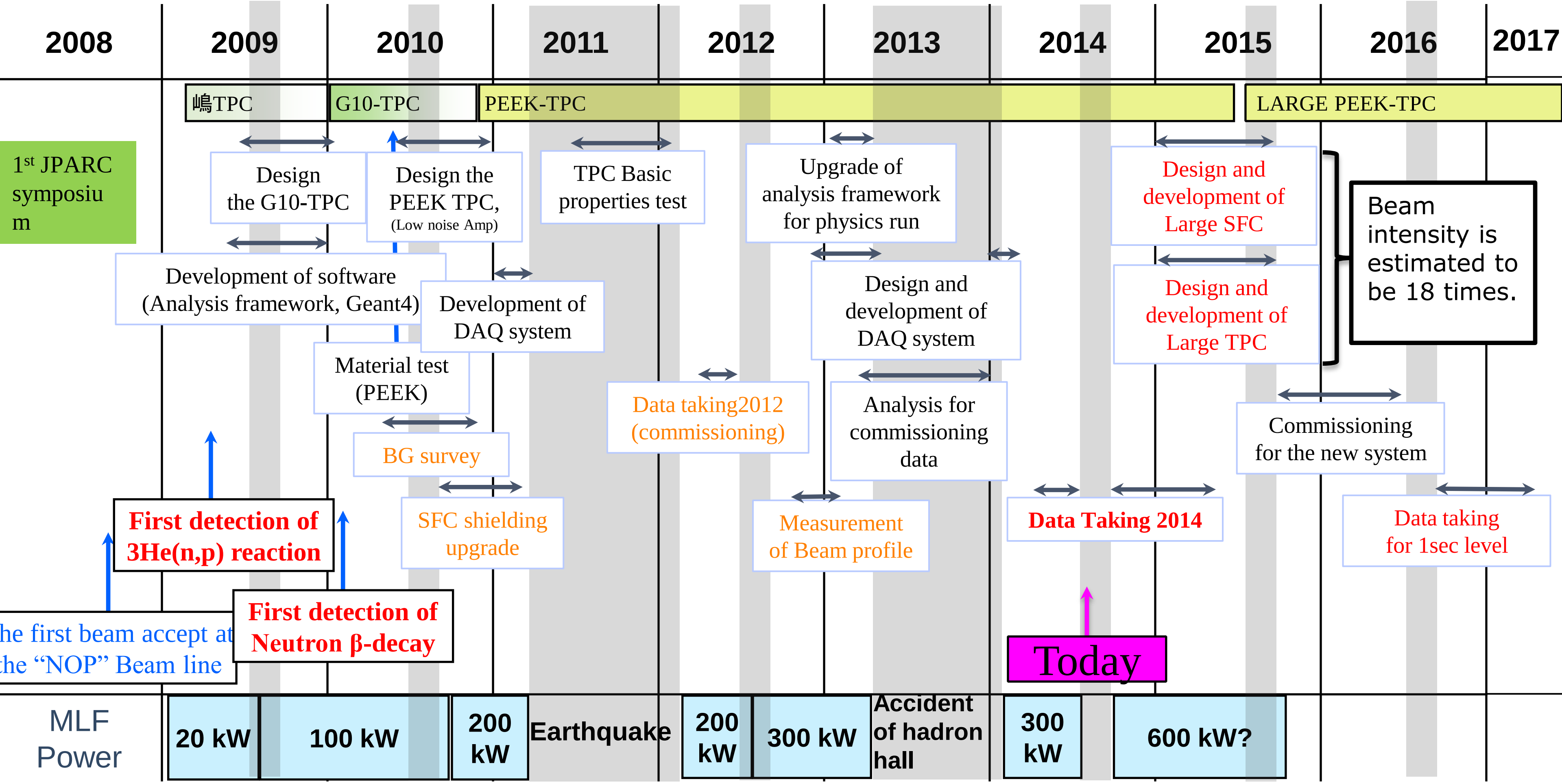
DAQ

TPC in the
vacuum chamber

Inside of
Lead shielding

Inside of
Cosmic ray Veto

chronological table



2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

嶋TPC

G10-TPC

PEEK-TPC

LARGE PEEK-TPC

1st JPARC symposium

Design the G10-TPC

Design the PEEK TPC, (Low noise Amp)

TPC Basic properties test

Upgrade of analysis framework for physics run

Design and development of Large SFC

Design and development of Large TPC

Beam intensity is estimated to be 18 times.

Development of software (Analysis framework, Geant4)

Development of DAQ system

Design and development of DAQ system

Material test (PEEK)

BG survey

SFC shielding upgrade

Data taking2012 (commissioning)

Analysis for commissioning data

Measurement of Beam profile

Commissioning for the new system

Data Taking 2014

Data taking for 1sec level

First detection of 3He(n,p) reaction

First detection of Neutron β-decay

he first beam accept at the "NOP" Beam line

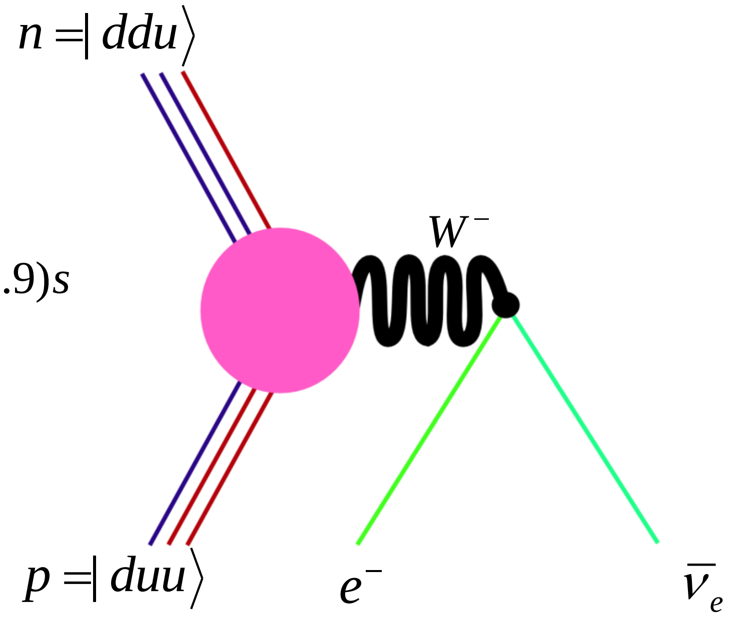
Today

MLF Power	20 kW	100 kW	200 kW	Earthquake	200 kW	300 kW	Accident of hadron hall	300 kW	600 kW?

Increasing size the Spin Flip Chopper is planed at 2014/2015.
Intensity will be 18 times by a designed value.
We will start physics run to 1sec at 2016/2017

The NIST Beam Lifetime Experiment II (BL2)

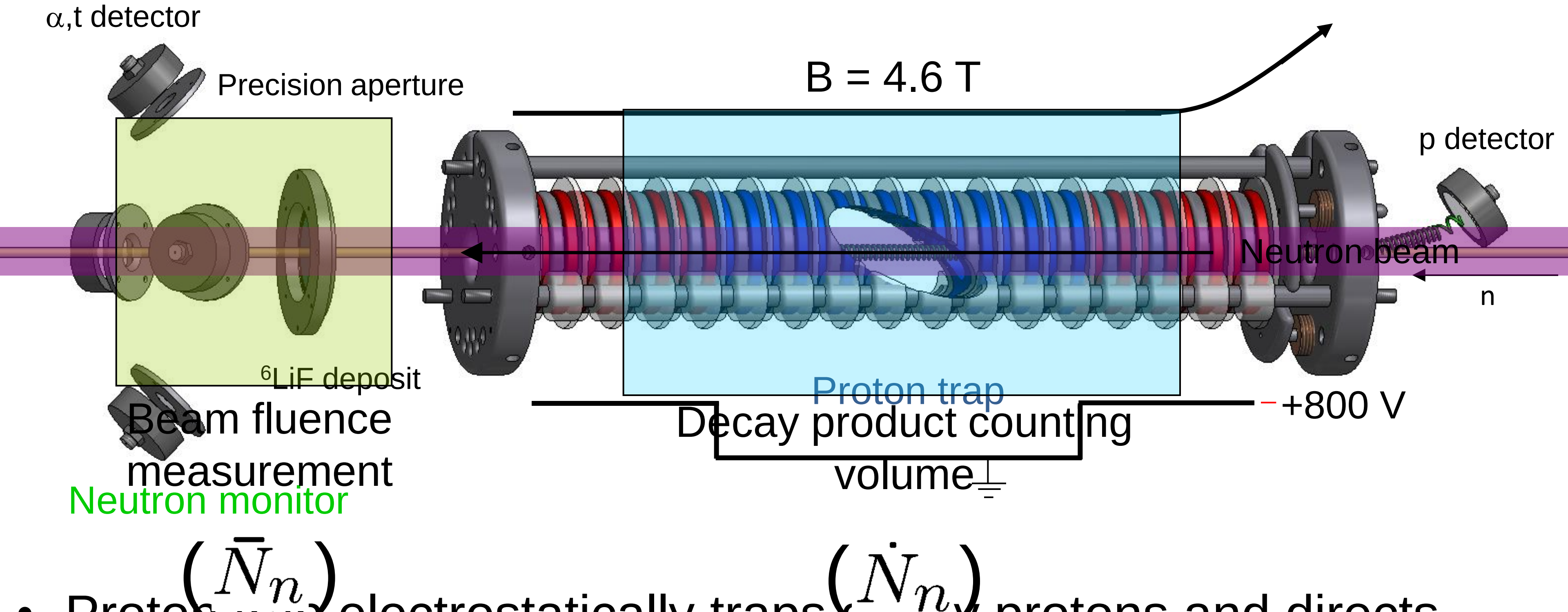
$$\tau_n = \frac{G_F^2}{G_V^2 + 3G_A^2} 4908.7(1.9)s$$



National Institute of Standards and Technology Physical Measurement Laboratory

The NIST beam lifetime experiment

$$\tau_n = -\bar{N}_n / \dot{N}_n$$



- Proton trap electrostatically traps decay protons and directs them to detector via B field
- Neutron monitor measures incident neutron rate by counting n + ^{6}Li reaction products (α + t)

Determining τ_n

$$\tau_n = \dot{N}_{\alpha+t}\left(\frac{L}{\dot{N}_p}\right)\frac{\epsilon_p}{\epsilon_0 v_0}$$

$\frac{L}{\dot{N}_p}$	Proton rate measured as function of trap length
ϵ_p	Proton detection efficiency
$\dot{N}_{\alpha+t}$	n + ^{6}Li reaction product counting
ϵ_0	Neutron flux monitor efficiency for v_0

NIST 2005 Error Budget

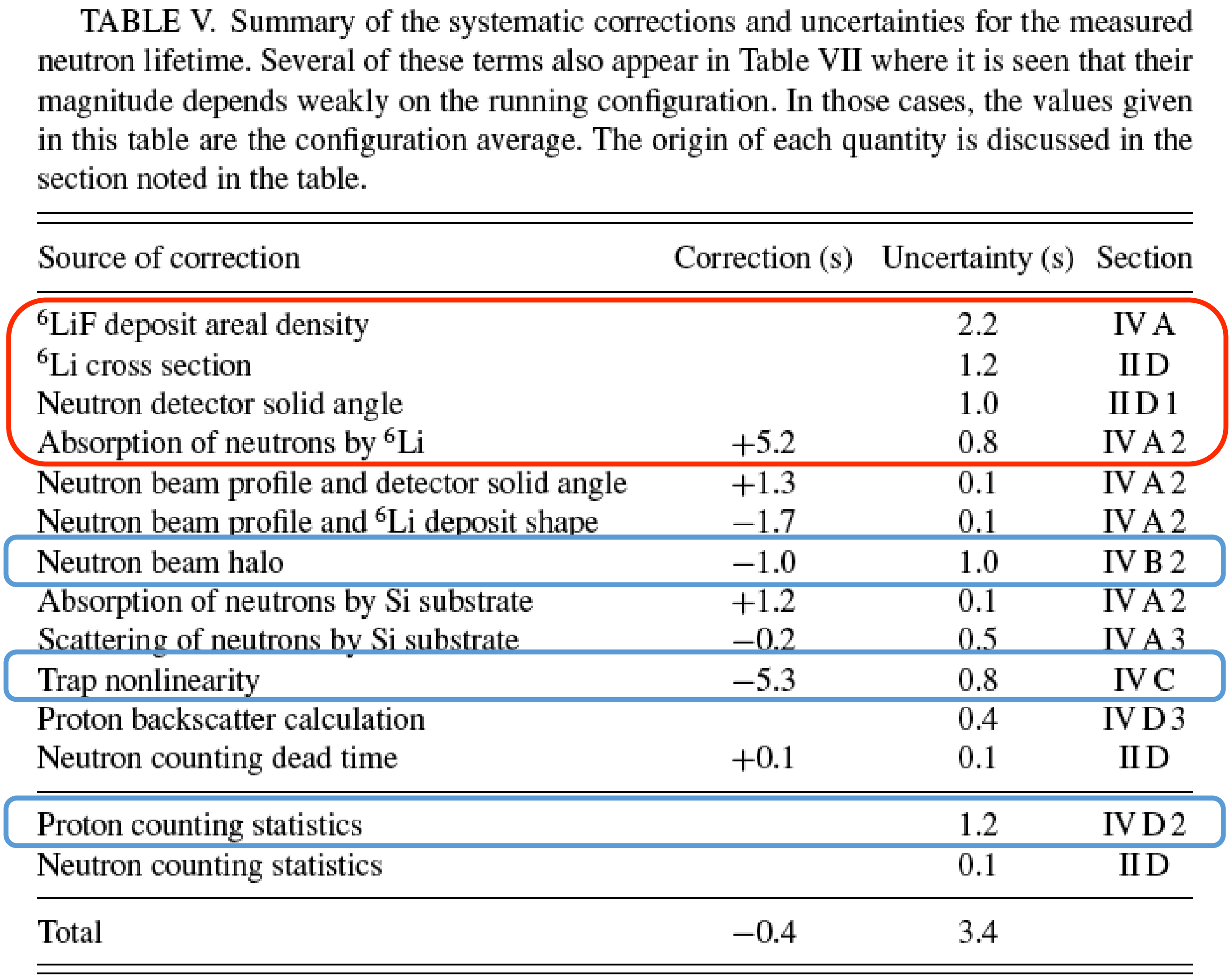


TABLE V. Summary of the systematic corrections and uncertainties for the measured neutron lifetime. Several of these terms also appear in Table VII where it is seen that their magnitude depends weakly on the running configuration. In those cases, the values given in this table are the configuration average. The origin of each quantity is discussed in the section noted in the table.

Source of correction	Correction (s)	Uncertainty (s)	Section
^{6}LiF deposit areal density		2.2	IV A
^{6}Li cross section		1.2	II D
Neutron detector solid angle		1.0	II D 1
Absorption of neutrons by ^{6}Li	+5.2	0.8	IV A 2
Neutron beam profile and detector solid angle	+1.3	0.1	IV A 2
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1	IV A 2
Neutron beam halo	−1.0	1.0	IV B 2
Absorption of neutrons by Si substrate	+1.2	0.1	IV A 2
Scattering of neutrons by Si substrate	−0.2	0.5	IV A 3
Trap nonlinearity	−5.3	0.8	IV C
Proton backscatter calculation		0.4	IV D 3
Neutron counting dead time	+0.1	0.1	II D
Proton counting statistics		1.2	IV D 2
Neutron counting statistics		0.1	II D
Total	−0.4	3.4	

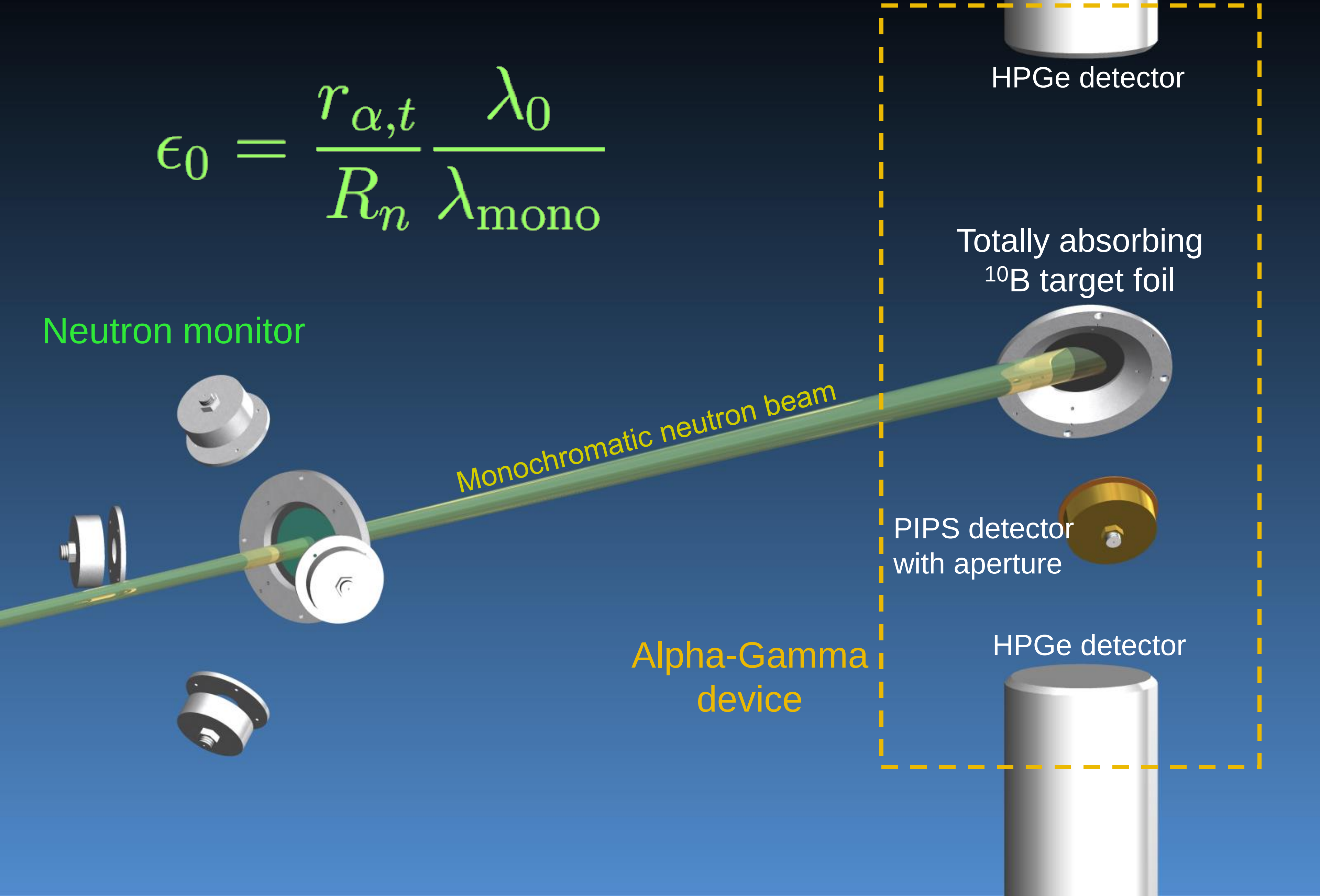
Most significant improvement

Other major improvements

Nico et al Phys. Rev. C **71** 055502 (2005)

Using AG to calibrate the neutron monito

$$\epsilon_0 = \frac{r_{\alpha,t}}{R_n}\frac{\lambda_0}{\lambda_{\mathrm{mono}}}$$



HPGe detector

Totally absorbing
^{10}B target foil

Neutron monitor

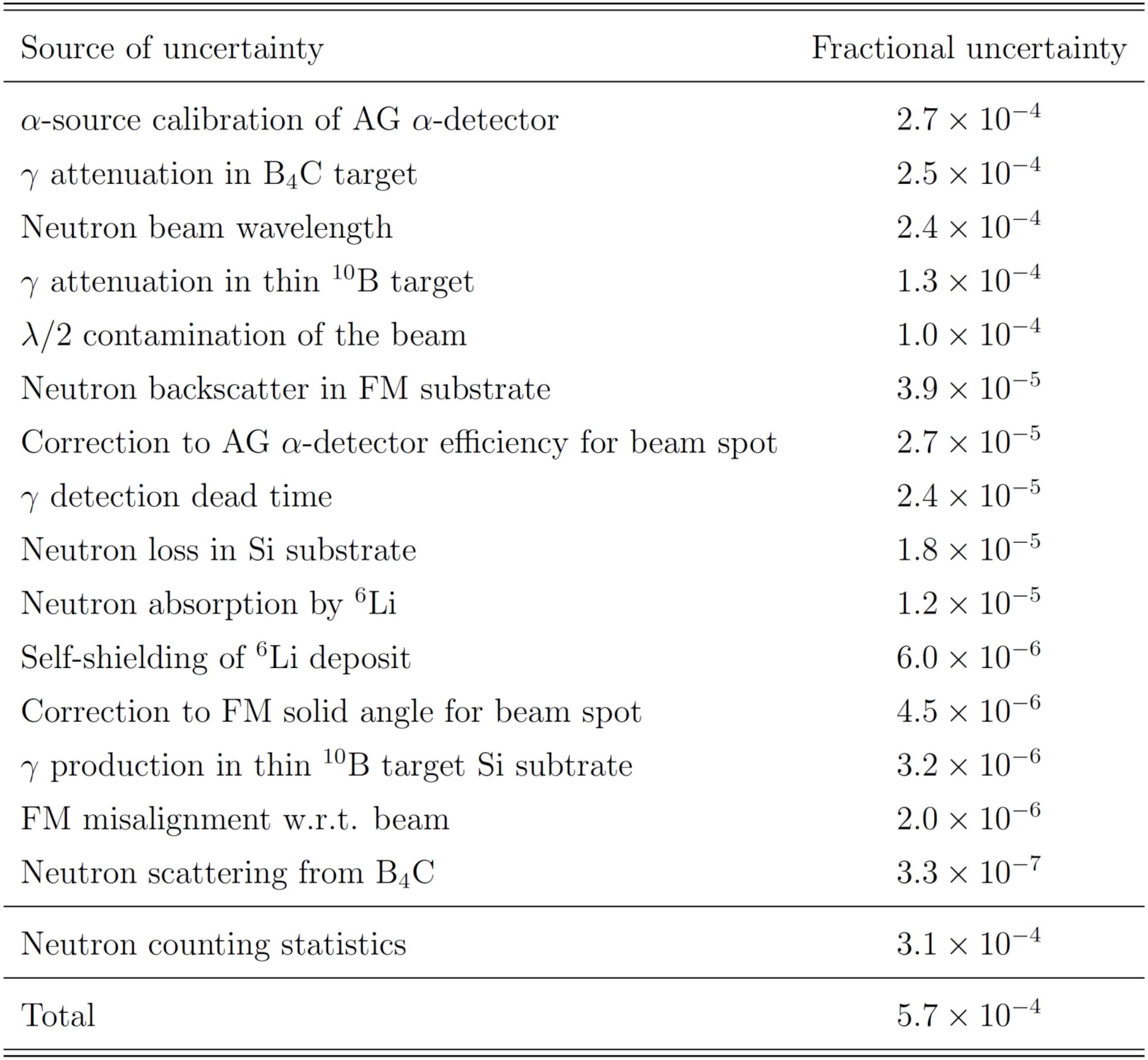
Monochromatic neutron beam

PIPS detector
with aperture

Alpha-Gamma
device

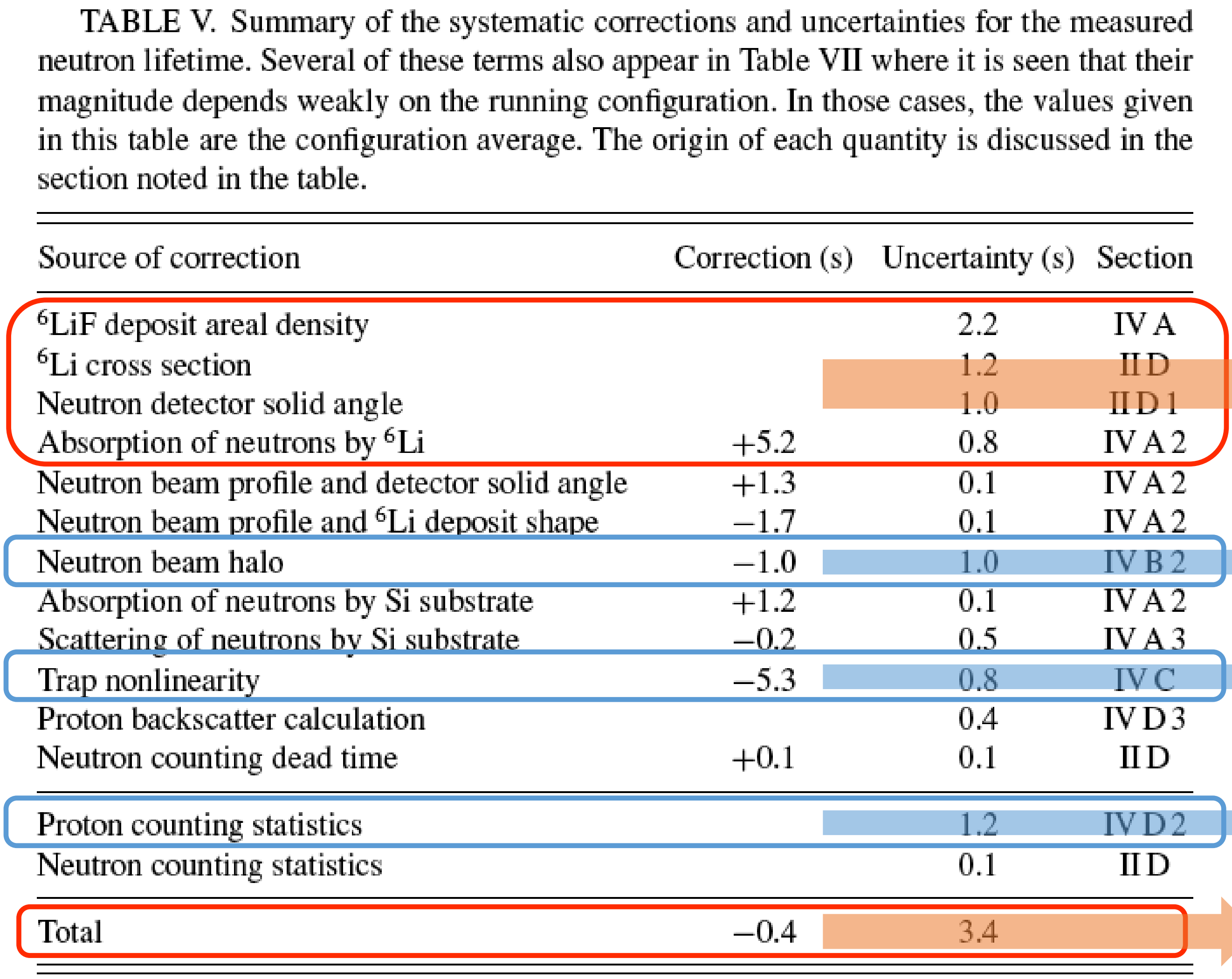
HPGe detector

Neutron monitor efficiency uncertainty budget



Source of uncertainty	Fractional uncertainty
α-source calibration of AG α-detector	2.7×10^{-4}
γ attenuation in B_4C target	2.5×10^{-4}
Neutron beam wavelength	2.4×10^{-4}
γ attenuation in thin ^{10}B target	1.3×10^{-4}
$\lambda/2$ contamination of the beam	1.0×10^{-4}
Neutron backscatter in FM substrate	3.9×10^{-5}
Correction to AG α-detector efficiency for beam spot	2.7×10^{-5}
γ detection dead time	2.4×10^{-5}
Neutron loss in Si substrate	1.8×10^{-5}
Neutron absorption by ^6Li	1.2×10^{-5}
Self-shielding of ^6Li deposit	6.0×10^{-6}
Correction to FM solid angle for beam spot	4.5×10^{-6}
γ production in thin ^{10}B target Si subtrate	3.2×10^{-6}
FM misalignment w.r.t. beam	2.0×10^{-6}
Neutron scattering from B_4C	3.3×10^{-7}
Neutron counting statistics	3.1×10^{-4}
Total	5.7×10^{-4}

Projected Error Budget (BL2)



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Proton counting statistics		1.2	IV D 2
Neutron counting statistics		0.1	II D
Total	−0.4	3.4	

Most significant improvement

Other major improvements

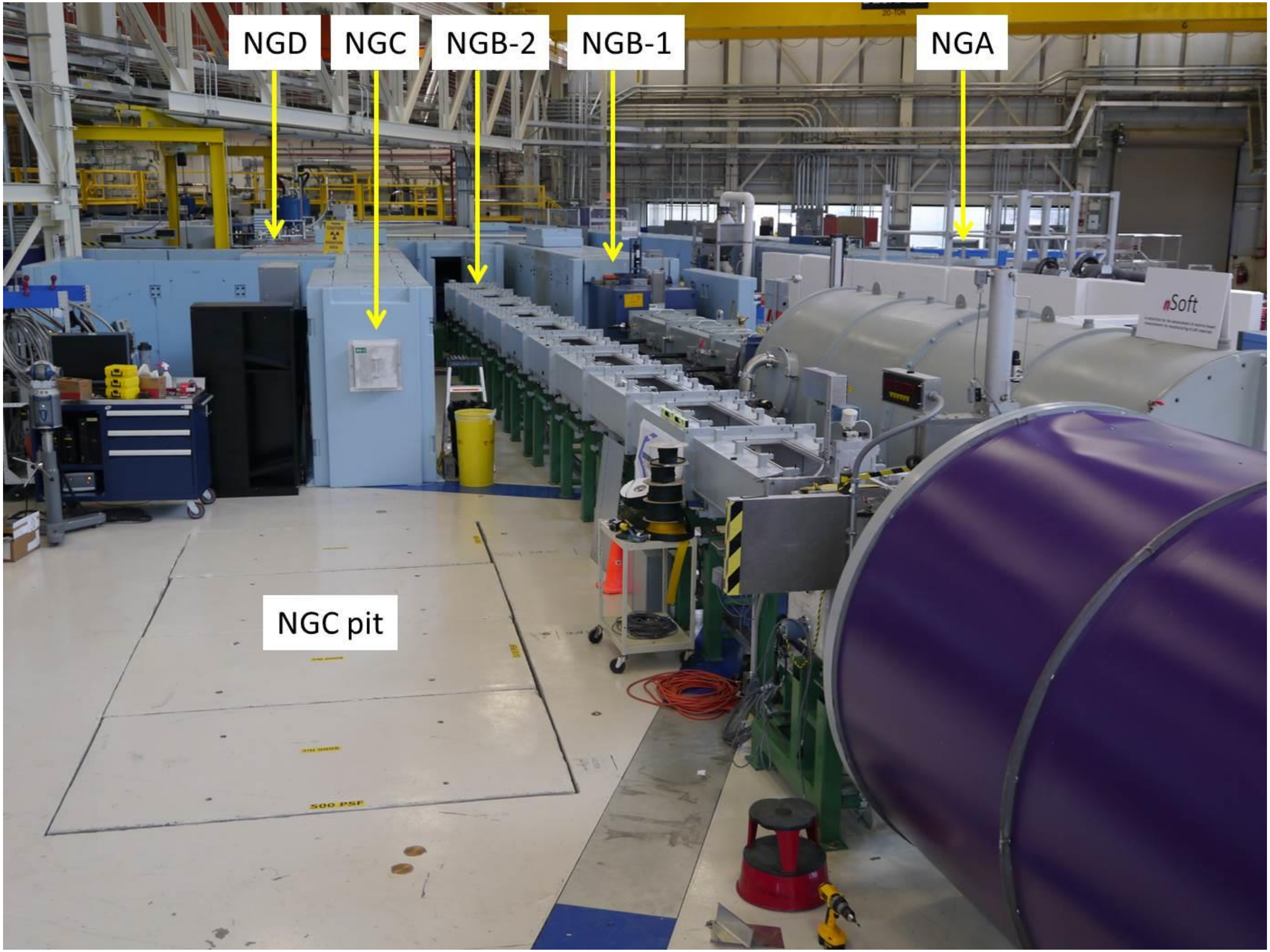
0.5s

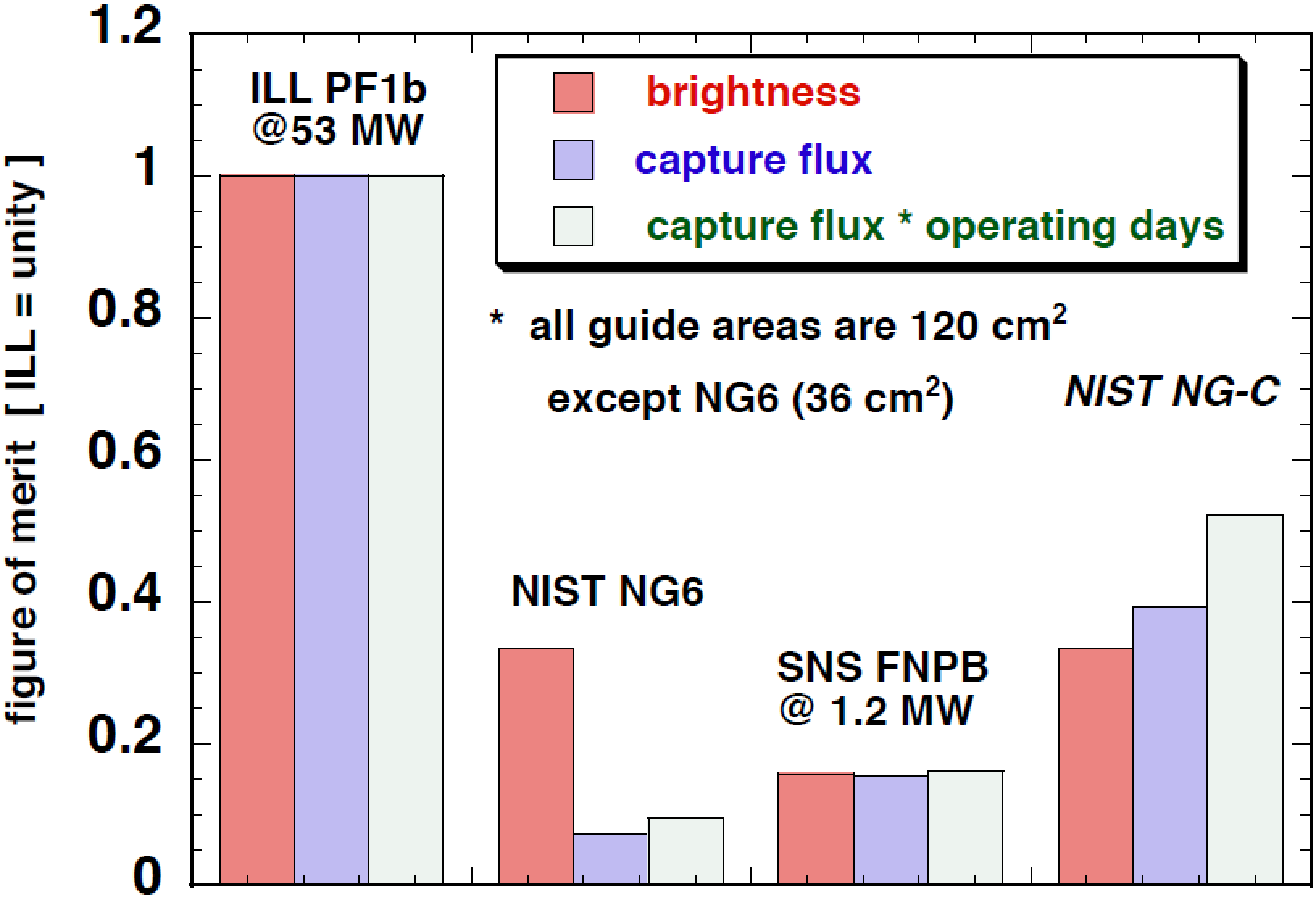
0.1s

0.2s

0.6s

$\delta\tau_n \approx 1.0s$


NGD
NGC
NGB-2
NGB-1
NGA
nSoft
NGC pit
500 PSF



* all guide areas are 120 cm^2

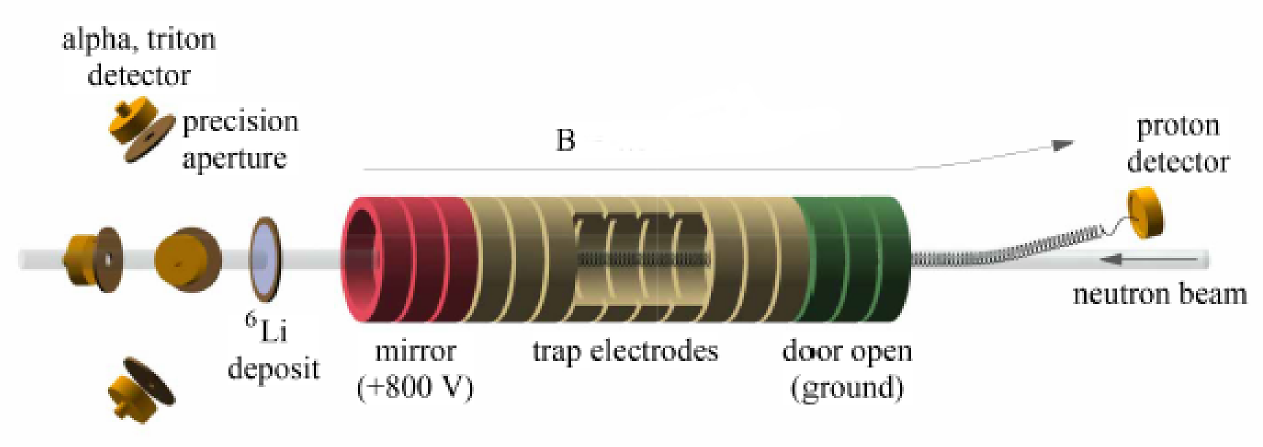
except NG6 (36 cm^2)

The Future

BL3

Beam Lifetime 3

The next generation beam neutron lifetime experiment



Two main goals:

1) Cross check, explore, verify all systematic effects in the beam method to the 0.1 s level
2) Reduce the beam neutron lifetime uncertainty to < 0.2 s.

University of Tennessee

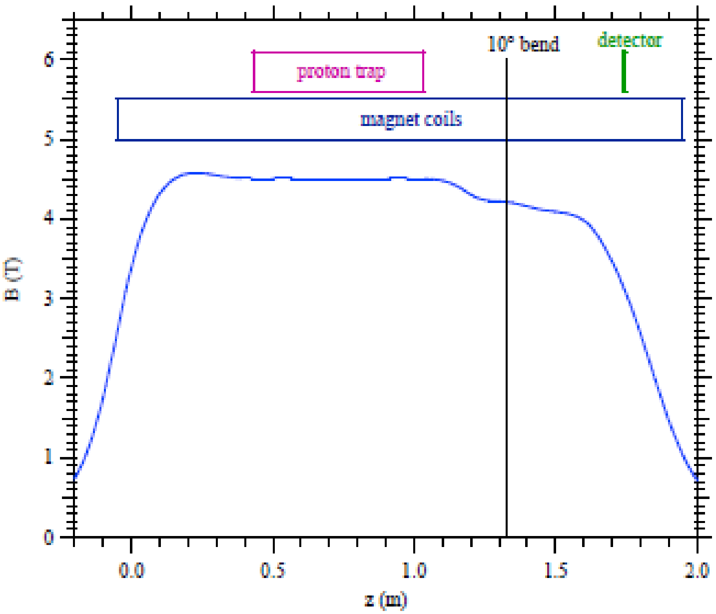
Tulane University

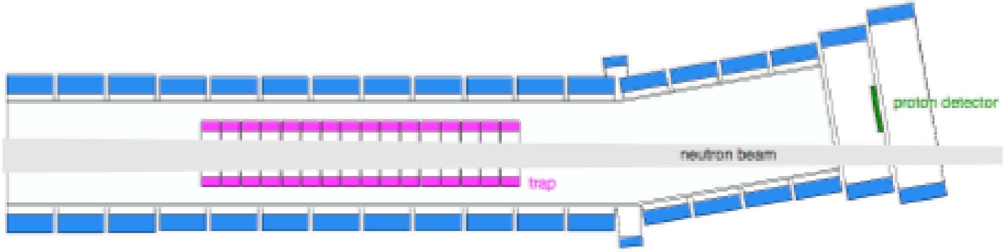
Indiana University

NIST
National Institute of Standards and Technology

BL3 key features:

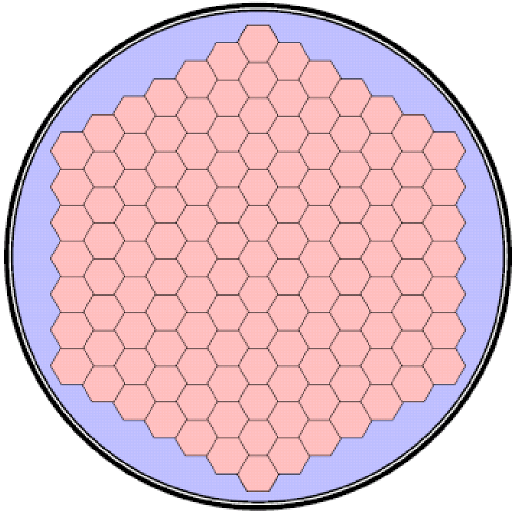
- **Based on previous Sussex-ILL-NIST apparatus; >30 years experience in this program.**
- **Larger beam, trap, 2m long magnet: 200x increase in proton trapping rate.**
- **10 cm active diameter segmented Si detector (Nab, UCNB).**
- **ΔB/B < 0.001 in proton trap region: reduces trap end effects.**
- **Variable field expansion at proton detector: eliminates backscatter extrapolation.**
- **Dedicated neutron spectral measurement: reduces Li6 self absorption uncertainty.**
- **Multiple independent absolute neutron flux calibrations.**

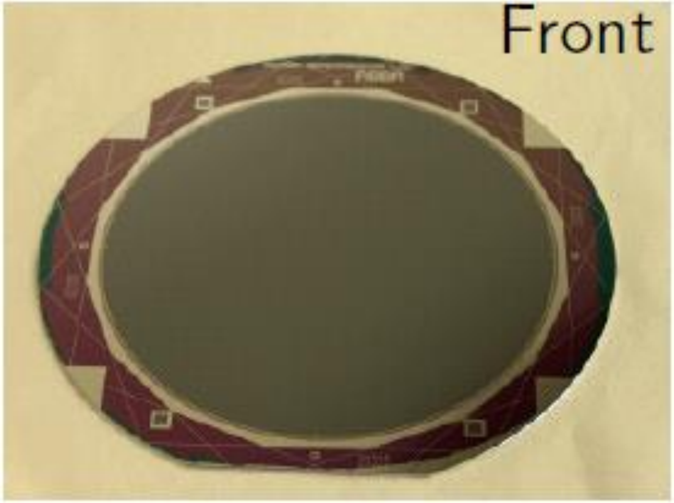




Nab Si detectors

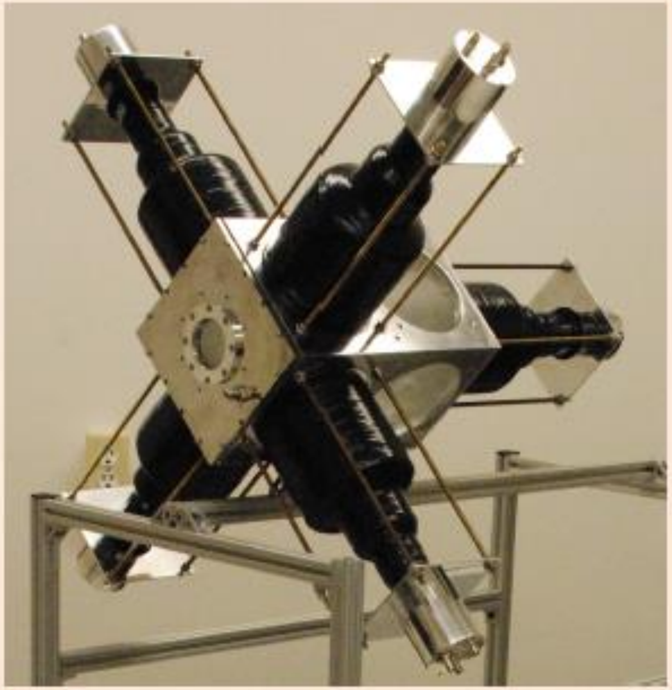
- 15 cm diameter
- Full thickness: 2 mm
- Dead layer ≤ 100 nm
- 127 pixels

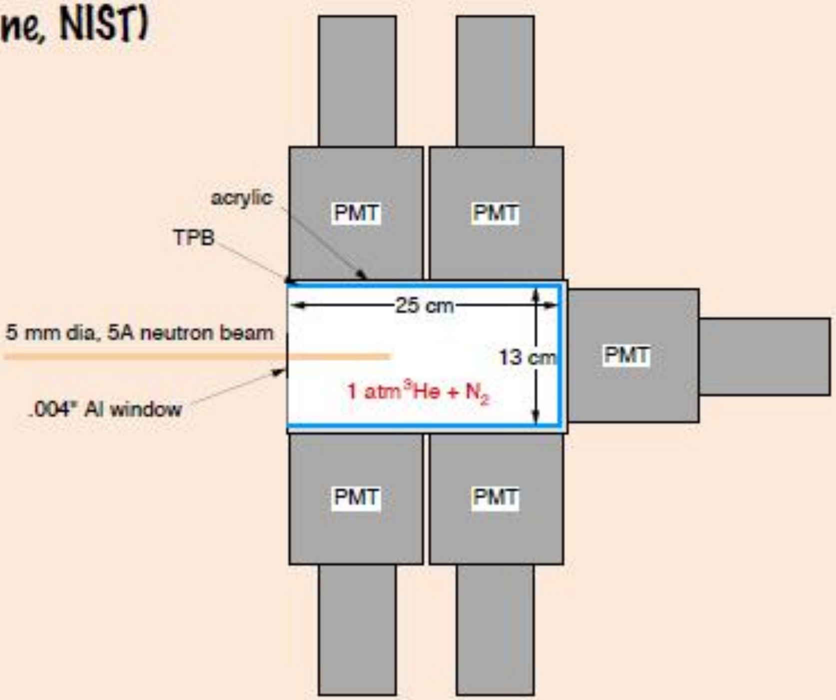




A ^{3}He gas scintillation absolute neutron counter

(Tulane, NIST)





Design features:

- absolute neutron counting to 99.95%
- >50 kHz pulse counting rate
- >30 photoelectrons/neutron capture
- ^{3}He gas scintillates in XUV (70-90 nm)
- XUV downshifted to visible by TPB
- 1-10 torr N_2 quenches long-lived triplet dimers

construction / testing now in progress

Conclusions

- Moving forward the goal is a reliable measurement of the neutron lifetime at the 0.1—0.2 s level
- It is likely that there will be two efforts in the US during the coming decade
  - BL3: a beam experiment designed to achieve an uncertainty of < 0.2 s.
  - UCNtau: a magnetic bottle experiment
- Both experiments will be seeking funding in the next 1—2 years